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Correction of Altitude-Induced Changes in Performance of the Volumetric Diffusive Respirator

Thomas Blakeman, MSc RRT

April 2017

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14. ABSTRACT
Aeromedical transport of critically ill patients requires continued, accurate performance of equipment at altitude. Changes in barometric pressure with increasing altitude are associated with alterations in gas temperature, density, and humidity that can change the performance of mechanical ventilators at altitude. The volumetric diffusive respirator (VDR-4, Percussionaire, Sandpoint, ID) high-frequency ventilator is used by U.S. military medical transport teams for critically ill patients with acute respiratory failure. Measured parameter settings varied widely among subjects and among individual settings at ground level and after changes were made at altitude. All 10 subjects made adjustments to the set parameters at altitude. The use of the Monitron II did not result in greater accuracy when adjusting settings. The VDR-4 is used in some circumstances with patients who have hypoxic respiratory failure despite the inability to accurately measure tidal volumes. The addition of the Monitron II monitor may help the caregiver more accurately set and monitor timing and pressure settings due to the digital readout. A method to measure and monitor tidal volumes is paramount to patient safety.

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1.0 SUMMARY

Aeromedical transport of critically ill patients requires continued, accurate performance of equipment at altitude. Changes in barometric pressure with increasing altitude are associated with alterations in gas temperature, density, and humidity that can change the performance of mechanical ventilators at altitude. The volumetric diffusive respirator (VDR-4, Percussionaire, Sandpoint, ID) high-frequency ventilator is used by U.S. military medical transport teams for critically ill patients with acute respiratory failure. Measured parameter settings varied widely among subjects and among individual settings at ground level and after changes were made at altitude. All 10 subjects made adjustments to the set parameters at altitude. The use of the Monitron II did not result in greater accuracy when adjusting settings. The VDR-4 is used in some circumstances with patients who have hypoxic respiratory failure despite the inability to accurately measure tidal volumes. The addition of the Monitron II monitor may help the caregiver more accurately set and monitor timing and pressure settings due to the digital readout. A method to measure and monitor tidal volumes is paramount to patient safety.

2.0 INTRODUCTION

Aeromedical transport of critically ill patients requires continued, accurate performance of equipment at altitude. Changes in barometric pressure with increasing altitude are associated with alterations in gas temperature, density, and humidity. These changes can affect the performance of mechanical ventilators calibrated for operation at sea level. Effects of increasing altitude include changes in the movement of gas through fixed orifices, altering accuracy in ventilator settings, as well as the measurement of flow and volume. The volumetric diffusive respirator (VDR-4, Percussionaire, Sandpoint, ID) high-frequency ventilator is used by U.S. military medical transport teams for critically ill patients with acute respiratory failure. Our previous bench study of the VDR at altitude demonstrated that the positive end expiratory pressure increased by 75% as a consequence of an increase to a simulated altitude of 8000 feet. This was coupled with an increase in the peak pressure equivalent to the increase in peak airway pressure. A method of correcting the changes caused by the change in altitude is likely necessary to improve patient safety.

3.0 METHODS

The VDR-4 is a pneumatically powered and pneumatically controlled device commonly classified as a high-frequency percussive ventilator [1]. The breath delivery allows a set pressure, positive end-expiratory pressure (PEEP)/continuous positive airway pressure, percussive frequency, and inspiratory and expiratory time. The breath delivery is accomplished through a spring-loaded, sliding venturi (Phasitron®, Percussionaire, Sandpoint, ID) connected to the endotracheal tube. The action of the venturi is to deliver a series of high-frequency pulses from the ventilator, building to a plateau pressure. The positive pressure delivery of each percussive pulse is followed by a passive fall in pressure as the spring moves the venturi back in to an expiratory position. The control mechanisms of the VDR-4 include a combination of a needle valve and a normally open cartridge. The movement of gas to and from this control system relies on the movement of gas through known restrictions and changes in pressure on opposing sides of

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a diaphragm. Figure 1 shows typical flow and airway pressure waveforms generated by the device.

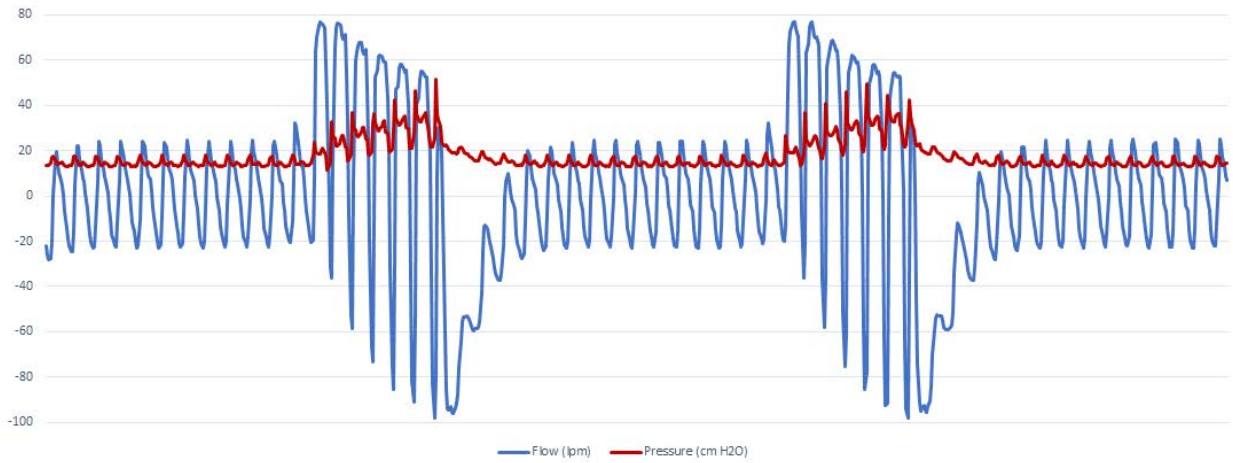

Figure 1. Typical flow and airway pressure generated by the VDR-4.

Airway pressure is monitored by an integral digital pressure gauge, which is connected via standard tubing to the proximal airway (Figure 2). This gauge also displays respiratory rate, frequency, amplitude, and PEEP. A secondary measurement of pressure can be accomplished by using the Monitron II Wave Form Analyzer (Percussionaire, Sandpoint, ID). This device uses a standard physiologic pressure transducer, which is able to measure the pressure more accurately and with faster response time. This device chooses the highest pressure during the percussive breaths as the "PEEP." Figure 3 shows Monitron II with a waveform displayed, attached to the VDR-4.

Figure 2. Integrated digital pressure gauge, connected via standard tubing to the proximal airway, used to monitor airway pressure.

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Figure 3. Monitron II with a waveform displayed, attached to the VDR-4.

Eight respiratory therapists and two physicians from U.S. military medical transport teams who have aeromedical transport experience using the VDR-4 volunteered to participate in the study. The study was approved by the University of Cincinnati and Wright-Patterson Air Force Base Institutional Review Boards. A test lung (TTL, Michigan Instruments, Grand Rapids, MI) was set at a compliance of 20 mL/cm H_2O and airway resistance of 5 cm H_2O/L/s. A pneumotachograph (PF 301, IMT Medical, Buchs, Switzerland) was placed between the VDR-4 circuit and test lung. Flow, volume, and pressure signals were continuously measured and recorded to a computer for later analysis.

Study subjects were asked to set up the VDR-4 using the following settings: frequency – 400 cycles/min, amplitude – 30 cm H_2O, PEEP – 10 cm H_2O, inspiratory time – 1.0 second, expiratory time – 2.0 seconds, respiratory rate – 20 bpm. At ground level after 5 minutes of stabilization, 10 minutes of data were recorded. After ascending to 8000 feet simulated altitude in an altitude chamber at Wright-Patterson Air Force Base, Ohio, the subjects were allowed to make changes to the previously entered settings if desired. The subjects were allowed to use the digital gauge, the Monitron II, or both to determine if changes were needed to achieve the same ventilator output after ascent to altitude as at ground level. After changes, if any, were made, the device was allowed to stabilize for 5 minutes and then output was recorded for an additional 10 minutes.

4.0 RESULTS

Measured parameter settings varied widely among subjects and among individual settings at ground level and after changes were made at altitude. All 10 subjects made adjustments to the set parameters at altitude. The use of the Monitron II did not result in greater accuracy when adjusting settings.

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5.0 DISCUSSION

High-frequency percussive ventilation with the VDR-4 is indicated for use in patients presenting with refractory hypoxemia and acute respiratory failure [2-9]. Most reports indicated that oxygenation was improved by using this modality. Theoretically, the rapid frequency and low volume of the percussive breaths are presumably lung protective, although there is no evidence to substantiate this belief. An important limitation of the VDR-4 is the lack of tidal volume measurement and display. Although the digital gauge integrated into the VDR-4 used in our study supplied more information than the devices with the aneroid gauge, the majority of the VDR-4 devices currently in use and those used by our study subjects use the aneroid gauge. Users rely on the change in pressure indicated on the gauge and past experience when attempting to adjust the device to provide the appropriate settings for the patient. Compounding the difficulty in setting the device, often changing one setting will have an effect on another setting. The integration of the Monitron II monitor provides a digital display of the device settings, but the pressures displayed are the highest pressures in a given portion of the breath cycle. For example, PEEP measurement during oscillation will vary and, depending on the set amplitude, PEEP displayed on the Monitron II may be greater than actual PEEP by 10 cm H_2O or more.

The evidence available for lung-protective ventilation dictates that tidal volumes be limited to 4-8 mL/kg of predicted body weight [10]. Our previous bench work with the VDR-4 at altitude showed that from ground level to 8000 feet, tidal volume increased 6-7% and PEEP increased by 40% with no change in any settings. Allan observed mean tidal volumes delivered by the VDR-4 of 1337 ± 700 mL when ventilating a model using acute lung injury conditions [11]. In a 70-kg patient, this would correspond to a tidal volume of 19.1 mL/kg as opposed to tidal volumes of 4-8 mL/kg recommended for lung protection. There have been reports of improvement in oxygenation and ventilation while using the VDR-4, but these reports do not list the tidal volume delivered to patients with acute respiratory distress syndrome and acute hypoxic respiratory failure [4,5]. Delivered tidal volume is not displayed on the device and is impossible to obtain without adding another measuring device to the patient circuit. Patients in the ARDSNet study [10] high tidal volume arm (12 mL/kg) showed better oxygenation and ventilation but died 22% more often than patients in the study arm that limited tidal volume to 6 mL/kg.

A previous study by the U.S. Army team described the successful use of the VDR for intercontinental transport. They found large differences in blood gases during flight, attributing these changes to function of the VDR. In a few cases, the partial pressure of carbon dioxide fell to well below safe values (<25 mmHg) [12]. Our findings suggest a second hypothesis that altitude changes result in large and potentially unsafe tidal volume delivery.

In this current study, delivered tidal volume was measured by an external pneumotachograph that allowed the study team to record and compare tidal volumes before versus after the participants made changes at altitude, not a luxury caregivers are afforded during clinical practice. Tidal volume range was 392-1154 mL at ground level and 501-1139 mL at 8000 feet using the same settings. Although there was no tidal volume for the participants to target when setting the VDR-4, the data demonstrate a wide discrepancy that can be attributed to the inability to monitor tidal volumes. A device/method to monitor chest excursion could benefit the caregiver by providing a way to monitor patient tidal volume to mitigate the proven effects of high tidal volume on patient mortality.

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6.0 CONCLUSIONS

The VDR-4 is used in some circumstances with patients who have hypoxic respiratory failure despite the inability to accurately measure tidal volumes. The addition of the Monitron II monitor may help the caregiver more accurately set and monitor timing and pressure settings due to the digital readout. A method to measure and monitor tidal volumes is paramount to patient safety.

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LIST OF ABBREVIATIONS AND ACRONYMS

PEEP positive end-expiratory pressure

VDR volumetric diffusive respirator

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